

Age trends and correlations of growth and wood properties in clone of *Eucalyptus urophylla* × *E. grandis* in Guangdong, China

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Abstract: We assessed growth traits and wood properties of DH32-29, a clone of *Eucalyptus urophylla* × *E. grandis*, at age of two to six years in Guangdong in China. Analysis of variance of studied traits showed that there were significant differences (1% level) on all studied traits among ages except for wood basic density. Analysis of age trends of growth traits and wood properties revealed that rotation length of DH32-29 should be more than six years or longer. Phenotypic correlations among traits at individual ages indicated that correlations between growth traits were strongly positive. There was significant change in relationship between growth and wood basic density with increasing age, ranging from -0.03 to -0.54 at 2 and 5 year and 0.003 to 0.3 at 3, 4 and 6 year. Correlations between Pilodyn pin penetration and basic density measured on increment cores showed that Pilodyn could rank or group genotypes or sites into density classes, but failure to predict individual tree and individual clone.

Keywords: eucalypt; age trends; growth traits; wood properties; correlation; nondestructive methods

Introduction

Along with growth of the global population and decrease of native forest area and natural forests protected by governments,

tree plantations and agroforestry have become the basic source to meet the increasing demand for pulp and paper and wood products, particularly in developing countries (Xu and Dell 2002; Huang and Dell 2002; Danusevicius and Lindgren 2002; Kien et al. 2009). Eucalypt is a suitable tree species for supplying the wood on a long-term sustainable basis, characterized by fast-growing, well adaptability, short-rotation, excellent wood properties, vigorous hybrids, and large natural genetic populations (Xu and Dell 2002; Huang and Dell 2002; Danusevicius and Lindgren 2002; Kien et al. 2009). Since the 1980's, systematic genetic improvement programs for eucalypts have been coordinated by the Dongmen project (1981–1989). This project was established under the Australia-China Program of Technical Cooperation. It was the first major attempt in China to test a wide range of the fast growing species under a range of silvicultural regimes on degraded soils (Simpson et al. 2002). Through more than 30 years of testing and domestication, eucalypts have experienced an important development in the subtropical and tropical zones in southern China. In China, the distribution range of eucalypts is from latitude 18°20' N (Sanya of Hainan) to 33° N (Hanzhong of Shanxi) and longitude 98°44' E (Baoshan of Yunnan) to 122°19' E (Putuo of Zhejiang), mainly including Guangdong, Hainan, Guangxi, Fujian, and Yunnan provinces, and its altitude distribution ranges from 4 m to 2400 m. Approximately 150,000 ha of new eucalypt plantations were established annually in China (Xu and Dell 2002; Qi et al. 2006). Indeed, more than 2 million ha of eucalypt plantations have been established with germplasm derived wholly from *Eucalyptus grandis* W. Hill ex maiden, *E. urophylla* S. T. Blake or from hybrids of this two species (Luo et al. 2010). Eucalypts, however, grow poor in southern India because of the tropical climate with mean annual rainfall of less than 1,000 mm and a long hot dry season of more than six months (Varghese et al. 2008). In the past the most widely planted eucalypt species in southern China were *E. exserta* F. Muell, *E. globulus* Labill. ssp. *globulus* and a hybrid of unknown origin known as *E. leizhou* NO.1 (Hardy et al. 2002).

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Forest trees are long-lived organisms and typified by long rotations and long breeding cycles. The expression of genes in relation to age and competitive environment is likely one of the most important features to consider in tree genetics and tree breeding (Kusnandar et al. 1998; Bouvet et al. 2003). However, short-rotation plantation management has been becoming a more and more important forest practice in many countries, particularly those lacking land or forest resources and with pressures from increasing populations and demands on forest products (Wei 2002). Eucalypt plantations in China have a much shorter rotation length, 4–5 years, compared with other regions where eucalypt rotations are from 6 to 8 or even 20 years depending on growth rates (Wei and Borralho 1996; Wei and Borralho 1999; Osorio et al. 2003; Stackpole et al. 2010; Luo et al. 2010). Wei and Borralho (1999) reported that breeding objectives for eucalypt plantations in China are also different from those developed for more industrialized countries in temperate regions in lower labor costs, higher land costs and higher fertilizer costs. The overwhelming majority of these fast-growing plantations of southern China are grown for the production of both fiber, to supply pulp mills or fiberboard factories, and small-diameter logs for veneer or even sawn timber (Wei 2002; Luo et al. 2010).

Clonal forestry requires estimation of basic parameters and genetic gains and provides the opportunity to capture both additive and non-additive genetic effects, and enhance both plantation productivity and product uniformity (Osorio et al. 2001; Osorio et al. 2003; Kien et al. 2010). The mean annual increment in volume of eucalypt plantations in China is less than the mean annual yield (more than $20 \text{ m}^3 \cdot \text{ha}^{-1} \cdot \text{a}^{-1}$) of eucalypt plantations in tropical and subtropical region of the parts of the world. Some commercial eucalypt plantations in countries such as Brazil, South Africa, Congo and Australia can be as much as $30\text{--}50 \text{ m}^3 \cdot \text{ha}^{-1} \cdot \text{a}^{-1}$ (Mo et al. 2002). Poor performance of eucalypt in China attributes to lack of genetically-improved planting material, generally degraded soil (Kien et al. 2009), poor quality of clones, and nonstandard afforestation (Mo et al. 2002). In China, eucalypt cultivation is based on a small number of clones (Pegg et al. 2006). These monoclonal or oligoclonal plantations of restricted genetic diversity carry potential risks of damage by disease or insect outbreaks or of inability to cope with extreme climatic conditions (Pliura et al. 2007). DH32-29 is a hybrid clone of *E. urophylla* \times *E. grandis* selected by Dongmen Forest Farm in the 1980s (Qi et al. 2006). It is widely planted in southern China due to its stable growth and well adaptability. The annual yield of this clone is frequently reported by more than $30 \text{ m}^3 \cdot \text{ha}^{-1} \cdot \text{a}^{-1}$ (Wu et al. 2011b).

Numerous studies have been conducted in an attempt to understand age trends in genetic parameters such as heritability (Wei and Borralho 1996; Wei and Borralho 1997; Osorio et al. 2001; Bouvet et al. 2003), but there are very few reports on the changing correlations for growth and wood properties with age (Stackpole et al. 2010). While the effectiveness of the Pilodyn for evaluating wood basic density in eucalypt families or clones is commonly reported (Greaves et al. 1996; Hansen 2000; Kien et al. 2008; Yin et al. 2008; Wu et al. 2010; Wu et al. 2011a; Wu et al. 2011b); however, there are few reports of analyzing why the

Pilodyn can not evaluate basic density in one eucalypt clone or individual tree.

The objectives of this study were to: (1) compare annual growth traits and wood properties in order to determine the rotation length of DH32-29, (2) look at the relationships between growth traits and wood properties with age trends, and (3) investigate the effectiveness of using Pilodyn to predict basic density in one clone. These information will be used to develop appropriate selection strategies for eucalypt breeding programs in southern China.

Materials and methods

Trial description

The data and samples were collected from Luokeng town of Jiangmen City in Guangdong ($22^{\circ}22'N$, $112^{\circ}52'E$). This region is affected by the north tropical monsoon climate, with annual mean temperature of $21.8^{\circ}C$ and annual mean rainfall of 1,800 mm. Mean January temperature, mean July temperature and minimum temperature at this region were $13.4^{\circ}C$, $28.3^{\circ}C$ and $0.3^{\circ}C$ respectively (Wu et al. 2011a). The red lateritic earth derived from sandstone contains $30 \text{ mg} \cdot \text{kg}^{-1}$ total N, $1 \text{ mg} \cdot \text{kg}^{-1}$ total P, $29 \text{ mg} \cdot \text{kg}^{-1}$ total K. The soil pH is 4.9. The dominant plants in the undergrowth of the eucalypt plantation of DH32-29 were *Dicranopteris pedata* (Honutt.) Nakaike, *Mussaenda pubescens* Ait and *Rhodomyrtus tomentosa* Hassk. Planting pits ($50 \text{ cm} \times 50 \text{ cm} \times 40 \text{ cm}$) were prepared and 0.5 kg compound fertilizer was applied. Spacing was $2.3 \text{ m} \times 2.5 \text{ m}$.

Data collection

Measurements and 5 mm diameter increment cores of 50 individual trees were collected from eucalypt plantations of DH32-29 by standard plot method in April 2010 at Luokeng town at age of 2 to 6 years respectively. Though the data was collected in different material, this method may appropriate to analysis different ages because of the same clone from neighboring area. Basic density (BD) was determined using the water displacement method (Wei and Borralho 1997; Kien et al. 2008; Wu et al. 2010), with two weights for every sample: volume of water displaced by immersion of wedge (w_1) and oven dry weight (w_2). Basic DEN was then calculated as: $\text{Basic DEN} (\text{g} \cdot \text{cm}^{-3}) = w_2 / w_1$

Diameter at breast over bark (DBHOB) and height (HGT) were measured for all trees. Individual tree volume over bark (V in m^3) was calculated using the following equation as per McKenney (1991):

$$V = \text{HGT} \times \text{DBHOB}^2 / 30,000$$

where DBHOB is diameter at breast over bark in centimeters and HGT is tree height in meters.

Pilodyn pin penetration (PPP) was measured using a 6-J Forest

Pilodyn fitted with a 2.5-mm steel pin, by removing a small section of bark (approximately 40 mm × 20 mm) at 1.3 m. We measured two Pilodyn readings in this bark window per tree, and a third measurement if the two first reading differed by more than 3 mm (Hansen 2000). PPP was recorded from two directions. The first was positioned at random, and the second was at right angle to the left or right of the first one.

Statistical analysis

The significance of fixed effects was assessed using F-tests. The analysis of variance was performed using the PROC ANOVA in SAS. Results for the individual ramets were subjected to variance analysis based on the follow linear model (Hansen and Roulund 1996; Jacques et al. 2002):

$$Y_{ij} = \mu + \alpha_i + \varepsilon_{ij} \quad (1)$$

where y_{ij} is the performance of the ramet of i^{th} age, and μ is the general mean, α_i is the random effect of the i^{th} age, and ε_{ij} is the random error.

Results and discussion

Analysis of variance of studied traits among different ages

The analysis of variance of studied traits among different ages is presented in Table 1. The results show that there were significant differences (1% level) on HGT, DBHOB, V and PPP among ages, with F value ranging from 29.68 to 95.59, indicating clear differences between ages. However, there were no significant differences in BD among ages in DH32-29, indicating that BD may be not the trait that decides the rotation length of DH32-29. The possible explanation could be at least due to the relatively stable properties on BD than other studied traits.

Table 1. Variance analysis of height (HGT), diameter at breast over bark (DBHOB), individual volume (V), basic density (BD) and Pilodyn pin penetration (PPP) among different ages

Source	DF	SS	MS	F Value	Pr > F
HGT (m)	4	1633.97	408.49	95.59	< 0.0001
DBHOB (cm)	4	628.86	157.21	38.59	< 0.0001
V (m ³)	4	0.27	0.07	57.60	< 0.0001
BD (g·cm ⁻³)	4	9.44	2.36	1.93	0.1063
PPP (mm)	4	312.20	78.05	29.68	< 0.0001

In southern China, eucalypts are grown mostly for pulp production (Wei and Borralho 1999). Meanwhile, volume production, wood basic density and pulp yield are three principal traits that drive the profitability of kraft pulp production (Greaves et al. 1997; Varghese et al. 2008). In general it is difficult to measure pulp production, so strong emphasis should be placed on volume production for determining the rotation length of DH32-29. Published studies in *E. urophylla* concluded that volume plays a dominant role in determining the economic benefits in fast-growing short-rotation plantation; meanwhile, wood quality

traits are also economically important in pulp production (Wei and Borralho 1999).

Age trends of growth and wood properties in clone of DH32-29

Mean values and ranges for growth traits and wood properties at five ages are presented in Table 2. Over the period studied, the V increased from 0.034 m³ at 2-year to 0.056 m³ at 3-year, 0.073 m³ at 4-year, 0.093 m³ at 5-year, and 0.130 m³ at 6-year. Meanwhile, the annual V increments were 0.022 m³, 0.017 m³, 0.02 m³ and 0.037 m³, respectively. This is relatively bigger than other studies in *E. urophylla* (Li et al. 2002), *E. camaldulensis* (Varghese et al. 2008; Kien et al. 2009) and *E. tereticornis* (Varghese et al. 2008). However the growth rate in our trials was lower than those reported in northern Tasmania where annual diameter increment was a mean of 17 mm at four years (Stackpole et al. 2010). For maximum site productivity, rotation age should be at the time when the peak of mean annual increment occurs (Mead 2005). Together with the above variance analysis, the results indicated that rotation length of DH32-29 should be more than six years or longer. Xu and Dell (2002) reported that the rotation period of eucalypt should be extended from the current 4-6 to 6-8 years because this rotation period will benefits both the economic position of the forest farmers and the maintenance of site fertility.

Table 2. Mean values and ranges for the studied traits at five years

Age	Traits	Mean	Min.	Max.	Std. Dev.	s.e.
2-year	HGT (m)	10.37	7.70	13.60	1.46	0.21
	DBHOB (cm)	9.67	6.60	12.00	1.32	0.19
	V (m ³)	0.034	0.011	0.065	0.013	0.002
	BD (g cm ⁻³)	0.391	0.338	0.443	0.022	0.003
	PPP (mm)	13.13	9.80	16.00	1.42	0.20
3-year	HGT (m)	12.65	7.90	15.00	1.57	0.22
	DBHOB (cm)	11.22	6.80	14.50	2.00	0.28
	V (m ³)	0.056	0.011	0.102	0.022	0.003
	BD (g cm ⁻³)	0.392	0.337	0.485	0.026	0.004
	PPP (mm)	12.98	10.10	16.25	1.29	0.18
4-year	HGT (m)	13.29	7.90	20.00	3.00	0.42
	DBHOB (cm)	12.37	8.20	18.50	2.16	0.31
	V (m ³)	0.073	0.017	0.188	0.037	0.005
	BD (g cm ⁻³)	0.422	0.344	0.480	0.025	0.004
	PPP (mm)	12.00	9.50	14.10	1.06	0.15
5-year	HGT (m)	15.41	11.50	18.40	1.80	0.25
	DBHOB (cm)	12.98	8.20	19.00	2.37	0.33
	V (m ³)	0.093	0.026	0.173	0.040	0.006
	BD (g cm ⁻³)	0.406	0.357	0.456	0.022	0.003
	PPP (mm)	13.53	9.50	15.50	1.07	0.15
6-year	HGT (m)	17.96	12.00	21.00	2.23	0.32
	DBHOB (cm)	14.38	9.60	18.30	2.16	0.30
	V (m ³)	0.130	0.042	0.223	0.049	0.007
	BD (g cm ⁻³)	0.445	0.384	0.538	0.030	0.004
	PPP (mm)	10.28	7.90	13.00	0.96	0.14

HGT= height, DBHOB=diameter at breast over bark, V = individual volume, BD = basic density, PPP = Pilodyn pin penetration, standard deviation = Std. Dev. and s. e. = standard error)

In accordance with the variance analysis, mean values of BD

increased from 0.391 g cm^{-3} at 2 year to 0.445 g cm^{-3} at 6 year. The results in our study were lower than that reported for *E. urophylla* at 3-year (Wei and Borralho 1997) and 10-year (Quang et al. 2009) and *E. Camaldulensis* at 3-year (Kien et al. 2009). However, the BD at 6 year was also below the most suitable range of basic density for pulpwood in eucalypts that has been suggested as 0.47 to 0.55 g cm^{-3} . Pulp yield has been shown to decrease sharply when basic density falls below 0.4 or exceeds 0.60 (Ikemori et al. 1986; Dean 1995; Kien et al. 2008).

Phenotypic correlations between studied traits and the effectiveness of using Pilodyn to predict BD in one clone

Phenotypic correlations among traits at individual ages are listed in Table 3. DBHOB and HGT had strongly positive phenotypic correlations with V, ranging from 0.60 to 0.99. The correlations between DBHOB and V, however, were higher than those between HGT and V on phenotypic levels, indicating the importance of DBHOB in selecting of improved stem volume. Correlations between DBHOB and HGT were significant at all ages. Therefore, DBHOB alone would be sufficient as a selection trait for growth, greatly reducing costs of measurement (Kien et al. 2009).

Table 3. Phenotypic correlations among traits at individual ages

Age	Traits	HGT	DBHOB	V	BD	PPP
2-year	DBHOB	0.71**				
	V	0.88**	0.94**			
	BD	-0.24	-0.03	-0.09		
	PPP	0.27	0.05	0.15	-0.21	
3-year	DBHOB	0.80**				
	V	0.84**	0.98**			
	BD	0.29	0.30*	0.34*		
	PPP	-0.13	-0.13	-0.12	-0.38**	
4-year	DBHOB	0.60**				
	V	0.82**	0.92**			
	BD	0.003	0.21	0.14		
	PPP	-0.27	-0.30*	-0.28*	-0.26	
5-year	DBHOB	0.94**				
	V	0.94**	0.99**			
	BD	-0.52**	-0.54**	-0.52**		
	PPP	0.11	0.06	0.01	-0.33*	
6-year	DBHOB	0.82**				
	V	0.87**	0.98**			
	BD	0.08	0.14	0.11		
	PPP	-0.19	-0.20	-0.20	-0.22	

Level of significance is denoted by: * = phenotypic correlations significant at 0.05 level; ** = phenotypic correlations significant at 0.01 level.

HGT= height, DBHOB=diameter at breast over bark, V = individual volume, BD = basic density, PPP = Pilodyn pin penetration.

The correlations between growth traits and BD were negative, ranging from -0.03 to -0.54, at 2 and 5 year whereas positive correlations were found between growth traits and BD, ranging from 0.003 to 0.3, at 3, 4 and 6 year. This is in agreement with

former findings. Stackpole et al. (2010) reported that there was significant change in relationship between growth and wood density with increasing age in *E. globulus* because trees that initially grow faster tend to produce less dense wood. Nevertheless Osorio et al. (2003) reported the opposite trend in *E. grandis* with an initial positive genetic correlation between height growth and wood density which declined with age toward zero.

Pilodyn, an indirect method for ranking genotypes or for grouping genotypes or sites into density classes (Moura et al. 1987; Raymond and MacDonald 1998), is effective in assessing large numbers of trees in eucalypts (Greaves et al. 1996; Wei and Borralho 1997; Hansen 2000; Kien et al. 2008; Yin et al. 2008; Wu et al. 2010; Wu et al. 2011b). The results in Table 3 showed that the correlations between BD and PPP were slightly negative, ranging from -0.21 to -0.33. This is in agreement with former findings concerning inaccuracy use for predicting individual tree. A possible explanation could be at least partially due to the low variation in BD in DH32-29 and relatively large errors in predicting BD by Pilodyn.

Major conclusions and implications

Joint analysis of all the findings of this study, important conclusions and implications as follows: First, rotation length of DH32-29 should be more than six years or longer because the fast-growing plantations are managed for pulpwood production on rotations as short as 4 years. Secondly, the correlations between growth traits and wood basic density were ranged from -0.03 to -0.54 at 2 and 5 year and 0.003 to 0.3 at 3, 4 and 6 year probably due to the competition between growth traits and wood basic density. Therefore, tending should be carried out at 2 and 5 year after plantation. Thirdly, eucalypt cultivation is based on a small number of clones in China, and it requires the breeding of multiple hybrids and clones. Finally, correlations between Pilodyn pin penetration and basic density measured on increment cores showed that Pilodyn could rank or group genotypes or sites into density classes, but failure to predict individual tree and individual clone.

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